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Thermally-Stimulated Current Investigation of Dopant-Related D^- and A^+ Trap Centers in Germanium for Cryogenic Detector Applications

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Thermally-stimulated current measurements provide a sensitive tool to characterize carrier traps in germanium detectors for dark matter search. Using this technique at cryogenic temperatures, very shallow traps have been detected with binding energies of a fraction of a meV, associated with the dopant species in the $D^-(A^+)$ charge states. A positive identification of these traps is achieved through an analysis of the field dependence of the carrier emission rates, which demonstrates a potential well for the trapped carriers in the form of a polarization well in r^{-4}, consistent with Lax's model for carrier trapping by a neutral center. The density of these traps is assessed, and implications for the space-charge cancellation procedure in cryogenic Ge detectors are discussed.

1. INTRODUCTION

Investigation of carrier traps in high-purity germanium has an interest of its own, and also because of its potential consequences for future developments in radiation detector technology.[1] Our interest in this context focuses in this paper on the dopant-related traps in cryogenic Ge detectors for dark matter search. Dopant impurities in Ge, whether of the donor (D) or the acceptor (A) type, are known to have different charge states: namely (i) the usual (D^+ and A^-) ionized state; (ii) the neutral state (D^0 and A^0) obtained by capture of an electron or a hole with a binding energy of ~ 10 meV typically, and (iii) the H^--like (D^- and A^+) state, obtained by capture of a

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second carrier.[2]

Because of their very small binding energies (a fraction of a meV only), the latter states are only observed at cryogenic temperatures (below a few hundred mK typically). We make use of the thermally-stimulated current (TSC) technique[3] to investigate these very shallow states of the dopant impurities. Section 2 presents the principle of the method and its implementation for measurements in a ^{3}He/^{4}He dilution refrigerator. In section 3 we determine the density and the binding energy of the traps, demonstrate an effect of field-enhanced emission whose analysis enables us to determine the form of the potential well of the traps, and obtain their capture cross-section for free carriers. Section 4 concludes with a discussion of these results in relation to the reset procedure in use for space-charge cancellation in Ge detectors at cryogenic temperatures.

2. PRINCIPLE OF TSC AND ITS IMPLEMENTATION FOR TRAP MEASUREMENTS AT CRYOGENIC TEMPERATURES

The principle of the TSC technique is to perform sequentially a trap filling operation, followed by a monitoring of the current transient associated with the thermal emission of carriers from the traps. The kinetics of carrier emission is monitored as a function of temperature and the voltage bias applied to the specimen. In our case, the experiment is made directly on a 200g detector of the Edelweiss collaboration. The device (ID203, *n*-type Ge with a net electrically active impurity concentration of 10^{11} cm^{-3})[†] and its experimental setup are described in a related paper in these proceedings.[4] Trap filling is performed optically using near-band edge infrared LED's (1.65 μm), so that electron-hole pairs are generated within the bulk of the Ge crystal.[5,6] Typical injection rates are $\sim$ 2x10^9 e-h pairs.s^{-1}.cm^{-3} for an integrated irradiation time of $\sim$ 10 s.

Carrier injection is performed with the collection electrodes all shorted to ground, in precisely the same way as is done in a detector reset (space-charge cancellation) operation.[5,6] The TSC data thus provide direct information on the density of the dopant species in the $D^-(A^+)$ states following a reset of the detector. Because electrons and holes are both injected simultaneously, the reset procedure has the consequence that the occupancies of the donor and the acceptor species are both varied at the same time. TSC data obtained in these conditions leave undecided whether the traps detected are acceptor or donor-related. Complementary experiments are planned to clarify this issue by varying the method of carrier injection.

[†] The crystal was provided by Umicore (Olen, Belgium).

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3. PROPERTIES OF THE DOPANT-RELATED TRAPS

(a) Signature of the traps. Figure 1 (a) presents a typical emission transient, measured at 400 mK under 24 V detector bias. The transient is recorded by inserting a picoammeter in the polarization circuit of the detector. The signal fits a simple exponential, from which the emission rate and the current amplitude I_0 at t = 0 are obtained. Figure 1 (b) presents the signature of the traps, in the form of an Arrhenius plot of the logarithm of the emission rate versus the reciprocal of the temperature. The activation energy for carrier emission, derived from the slope of this plot, is (0.75±0.02) meV, which is consistent with data from the literature for the binding energy of an electron at an arsenic impurity in the D^- state.[7] Because the experiment as performed does not distinguish between electron and hole traps, however, this conclusion is considered provisional only (see on this the remark at the end of sec. 2).

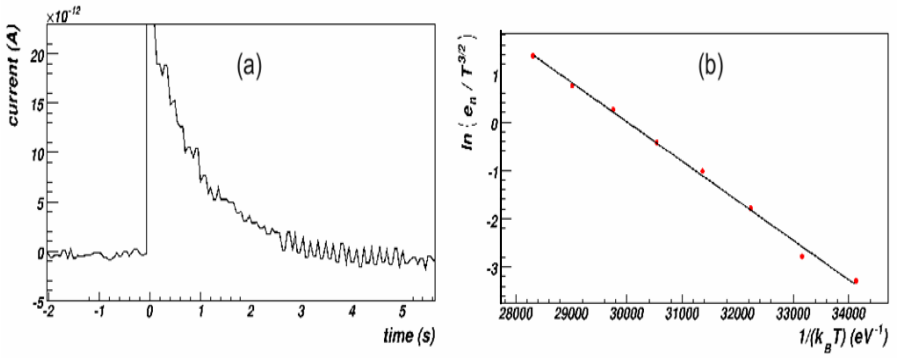

Fig. 1. (a) Current emission transient under 24 V detector bias (see text). The overshoot of the signal at t = 0 is an artifact of the measurement. (b) Arrhenius plot of the emission rate as a function of $1/k_BT$, giving the activation energy for carrier emission from the trap as E_t = (0.75±0.02) meV.

(b) Trap density. An application of Ramo's theorem[8] relates the current transient amplitude I_0 to the trap density N_t by the expression $I_0 = qN_tV_c/2\tau$, where q is the elementary charge, V_c is the volume of the detector crystal, and τ is the time constant of the emission transient. The trap density obtained is $N_t \sim 1.5\times10^7$ cm^{-3}. Due to the lack of uniformity of the illumination of the Ge crystal by the LED's in their present setup, this value is considered an order of magnitude only. The important fact is the very low density of the D^- (A^+) centers, as compared to the doping level of the specimen (10^{11} cm^{-3}).

Let us note in passing the extreme sensitivity of these TSC measurements, which makes them comparable to that of the deep level and the photo-induced current transient spectroscopies (DLTS and PICTS, respectively), as applied to electronic defects characterization in ultra-pure germanium.[9]

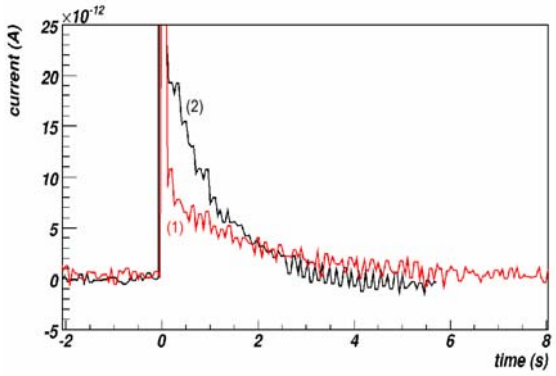

Fig. 2. Current transients at T = 410 mK for two different detector biases, showing the field effect on carrier emission. Transients (1) and (2) correspond to field intensities of 1.8 V/cm and 11 V/cm respectively (see text).

(c) Field-enhanced emission (Poole-Frenkel effect) and the potential well of the traps. Figure 2 presents two emission transients, both measured at T = 410 mK under different biasing conditions of the device, corresponding to a collection field of 1.8 V/cm and 11 V/cm respectively. The kinetics of carrier emission is seen to be enhanced by the field.[16] We analyze this field effect using Lax's model[10] for the polarization well of a neutral defect (in this case, a dopant impurity in the A^0 or D^0 state). The Coulomb interaction between a carrier and the electric dipole it induces on the neutral center results in an attractive potential in $1/r^4$, and the existence of a shallow bound state, which is the H^--like configuration of the defect. In the presence of an applied electric field, the energy barrier to emission is lowered by an amount of $AF^{4/5}$ where F is the electric field and A is a constant, $A = (5q/4)(\alpha q/8\pi^2\varepsilon^2)^{1/5}$, so that the emission rate has a dependence on the field in $\exp(-AF^{4/5}/k_BT)$.[11,12] In the expression for A, ε is the dielectric constant of Ge and α is the polarizability of the neutral impurity, $\alpha \approx \alpha_H(m_0/m_{eff})(E_H/E_t)^2$, with α_H the polarizability and E_H the ionization energy of the hydrogen atom, E_t that of the shallow trap (0.75 meV), and m_0 and m_{eff} the free electron and the effective electron or hole masses (depending on the nature of the trap). Assuming a D^- (electron) trap, a fit of our experimental data to

Lax's model gives for *A* a value of $(4.0\pm0.9)\times10^{-6}$ eV.$(V/cm)^{-4/5}$, to be compared with the theoretical value of 3.5×10^{-6} eV.$(V/cm)^{-4/5}$. Our results are thus consistent with the hypothesis that the traps investigated are dopant-related centers with a polarization potential well in r^{-4}.

(d) Temperature dependence of the capture cross-section. To obtain the capture cross-section σ_n, we make use of the expression for the emission rate $e_n = \tau^{-1}$:

$$e_n = \sigma_n v_{th} N_c \exp(-E_a/k_B T),$$

where v_{th} is the mean thermal velocity of an electron, N_c is the effective density of states in the conduction band, and E_a is the activation energy for emission (which is the trap energy E_t corrected for the electric field lowering of the barrier to emission).[13] Based on the experimental data for the temperature and the field dependencies of the emission rates, the values obtained for σ_n are in the range between 10^{-13} and 10^{-12} cm^2, which is of the order of magnitude expected from a theoretical modeling of electron capture by neutral donors in Ge in the temperature range of these measurements[14] (let us note the rather large uncertainty in σ_n as obtained by these measure-ements, which reflects that on E_a as determined by the signature of the traps).

4. DISCUSSION

An important issue in relation with these studies is the situation regarding the charge state of the impurities and crystal defects in a 'well-regenerated' state of the detector (by this is meant, a situation where the residual space-charge density is low enough that the charge collection efficiency of the device is reduced to ~ naught in the absence of an applied collection field). If we assume for the sake of simplicity that the only impurities contributing to the space-charge are the dopant species, and that the latter are of one type only (e.g., donors), then the crystal should be considered as populated by a random distribution of positively (D^+) and negatively (D^-) charged centers in equal densities $N_t \sim 10^7$ cm^{-3}, so that the space-charge density averages to zero on a scale of distances large compared with the mean spacing of the centers, ~ 50 μm. As pointed out in related papers in these proceedings,[4,15] however, this conclusion is at variance with the results of an analysis of the charge collection patterns of these devices, which implies a much higher density for the charged scattering centers, of up to several times 10^{10} cm^{-3} depending on crystal purity. A likely explanation for this discrepancy is that, rather than being associated with the dopant species, the scattering centers are related with deep level impurities or crystal defects, which makes them undetectable by our low-temperature TSC

measurements. Further investigations are planned to characterize the properties of the deep level traps in the detector crystals at cryogenic temperatures.

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